

## INFRASOUND SENSOR CALIBRATION AND RESPONSE

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### **ABSTRACT**

We will report on new developments that add improved functionality to the Los Alamos infrasound calibration chamber. Under separate funding a number of upgrades were made to the chamber. These include a Geotech Smart24 digitizer and workstation, an LVDT sensor for piston phase measurement, a Vaisala pressure and temperature sensor package, new motor controller for the mechanical piston phone, and a CLD electro-mechanical piston source, which can be driven by the calibration functions in the Smart24. This work greatly benefited from the expertise and collaboration of R. P. Kromer, Array Information Technology, Albuquerque, NM. We will discuss how the new features improve and extend the usefulness of the chamber for infrasound calibration. Additionally, plans for increased collaboration with Darren Hart, Sandia National Laboratory, on calibration issues and research will be discussed.

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### **OBJECTIVES**

This project supports the capability to perform accurate infrasound sensor calibrations using a piston source and large volume chamber whose output has been independently determined and for which the error budget has been accurately assessed. Since the mid 1980s, Los Alamos National Laboratory (LANL) has operated an infrasound sensor calibration chamber that operates over a frequency range of 0.02 to 4 Hz. This chamber has provided sensitivities, volts/Pa, for sensors used by Los Alamos and others. Under the current program we will restore the chamber function, interrupted by an unexpected move, collaborate with researchers at the Sandia National Laboratory (SNL) Facility for Acceptance, Calibration, and Testing (FACT) Site on sensor issues, calibrate sensors as needed and research new methods for sensor response determination.

### **RESEARCH ACCOMPLISHED**

#### **Background**

The Los Alamos infrasound calibration chamber, Figure 5, is a large volume concrete and steel, sealable, chamber equipped with a gear-driven, variable speed piston that has a fixed travel distance. The nominal output is a sinusoid of around 3.5 Pa peak –to-peak amplitude, and the larger interior volume is just under  $10^6 \text{ cm}^3$ . LANL was given the chamber by Ed Bullard, head of the original Chaparral Physics. (In the 1960s and 1970s, Mr. Bullard was involved in a variety of infrasound research and applications work in the El Paso, TX, area. Two of the important organizations were Globe Universal Sciences and Schellenger Research Laboratory at the University of Texas, El Paso.) More than one sensor may be calibrated in the chamber at the same time. The walls of the chamber are 4.5 inches thick and aid in the reduction of low-frequency external signals such as from passing weather systems. One can, from time to time, see effects of strong fronts at the lowest frequencies. This suggests that a better configuration would be to put the chamber in an isolated room inside a building. This provide better isolation.

As a calibration tool, the output of the piston source must be known. The piston output pressure,  $p$ , can be written as

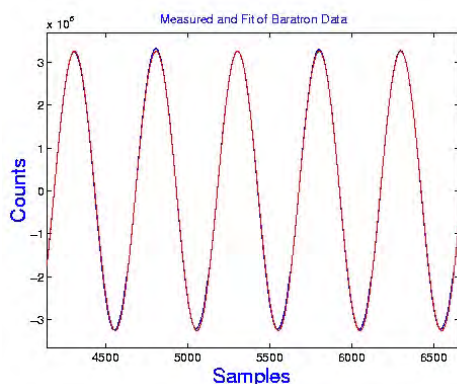
$$p = \frac{P_0 \gamma \delta V}{V_0} = C_{ch} P_0 \quad (1)$$

where  $P_0$  is the ambient pressure,  $V_0$  is the total system volume,  $\gamma$ , is the ratio of specific heats, and  $\delta V$  is the piston volume, depending on the piston area and travel distance, and  $C_{ch}$  then is the chamber constant. The equation above is correct as long as the air responds adiabatically and no non-ideal effects are in play. At lower frequencies these become more important. We will discuss this more in a later section. Clearly it is possible to establish the chamber constant through direct measurement of the physical components. A number of years ago we made measurements of the volumes and piston area and piston travel distance to derive the chamber constant.

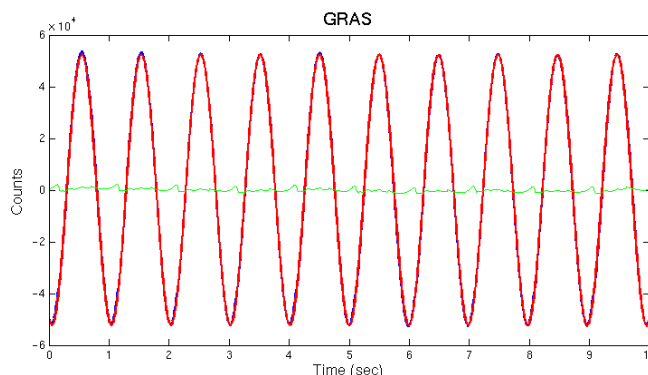
#### **More Recent Calibration Work**

The next step in determining the chamber constant involved the use of an MKS Baratron 698A sensor that had an independent calibration that was verified at the SNL Standards Lab. An output of 0.0 to 10.0 volts corresponded to 0.0 to 0.1 Torr (mm of Hg). The conversion from Pa to Torr is 133.3224 Pa equals 1.0 Torr. The chamber piston was operated at 0.04 Hz, and the signal was measured and recorded at 20 samples per second on a GeoTech Instruments DL 24 digitizer. Fifty cycles of data were fit with the Matlab function NLINFIT that gave the peak amplitude. A sample of the measured and fit data is shown in Figure 1. This gave a value of 4.143E-05 for the chamber constant,  $C_{ch}$  at 0.04 Hz. This value was within 2% of the value derived from the first dimensional measurements mentioned above. The Baratron unit could only be used at low frequency. (This work was presented at the 2001 Infrasound Technology Workshop in Hawaii.)

The next calibration measurements were made with a GRAS 40 AN low frequency microphone with an independent calibration from a standards laboratory in England. This unit was used over the frequency range of 1.0 to 4.0 Hz.



**Figure 1:** A portion of the measured (blue) and fit (red) MKS Baratron signal at 0.04 Hz, in the form of counts vs samples.



**Figure 2:** A portion of the calibration record for the GRAS microphone at 1 Hz covering 0 to 10 seconds on the x-axis and  $\pm 60,000$  counts on the y-axis. Blue are the data, red is the fit and green is the residual of the fit.

In doing the calibrations with the GRAS unit, we used a Martel calibrated voltage source to establish the bit weights of the DL 24 recorder we used in the runs with the GRAS sensor. The chamber constant at 4 Hz was  $4.446\text{E-}05$  using the calibrated GRAS microphone. This value is a bit larger than that derived with the MKS Baratron sensor, which is likely due to the influence of non-ideal effects that can be more significant at lower frequency.

Around this time Dr Harold Parks of the Primary Standards Laboratory at SNL began working with us to re-determine the chamber constant and to independently estimate the uncertainty in the determination. The first task was a new set of measurements of the chamber dimensions. The interior dimensions were made with an interior micrometer set that had been calibrated at the Sandia Mechanical Calibration Laboratory. Between 5 and 10 measurements were made of the chamber length, height and width and portal length and diameter. The piston travel distance was measured with a depth micrometer that was calibrated against a gauge block by the Sandia Primary Standards Laboratory. In measuring the geared piston, we found that there was a rubber boot (sleeve) around the piston that provided an airtight seal in the cylinder housing in which the piston moved and added a small amount to the piston area, potentially 8% in diameter. In the previous measurement, this small increment had not been included. In Figure 3 we show the four values for the chamber constant, where full boot refers to the most recent dimensional measurements and includes the maximum boot addition to piston area.

Dr Parks examined non-ideal effects and measurement errors and compiled an error budget, Parks (2007). The uncertainty in piston output is the largest contributor to the uncertainty and his summary is shown in Table 1. Adiabatic versus isothermal processes in the chamber were examined. His analysis of thermal conduction, without convection, showed that in the LANL chamber, at its operating frequencies,  $\gamma$  is very close to the adiabatic of 1.4, falling only to 1.38 at 0.02 Hz, and is shown in Figure 4. His analysis followed Gerber (1964a, 1964b), whose work used known solutions to the heat transfer equation by Carslaw and Jaeger (1959) and Hunt (1955).

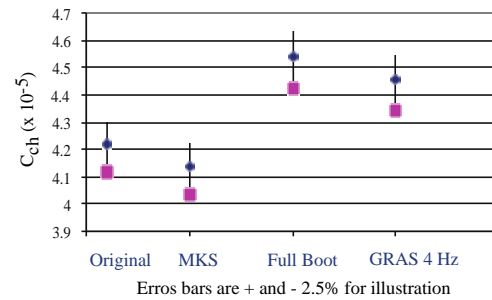
### Chamber Upgrades

While the chamber worked well there were improvements that could be made that would enhance functionality. Some of the upgrades included: a way to determine the position, phase, of the piston, a dedicated digitizer, piston frequency counter, better cabling, chamber pressure and temperature sensors and a variable output piston. In 2010 with support from US Space Missile Defense Command (SMDC) and the National Center for Physical Acoustics (NCPA) of the University of Mississippi, we began to install a series of upgrades to the chamber. The mechanical design and fabrication work were done by Mr. Richard Kromer, of Array Information Technologies, working with LANL under the SMDC support.

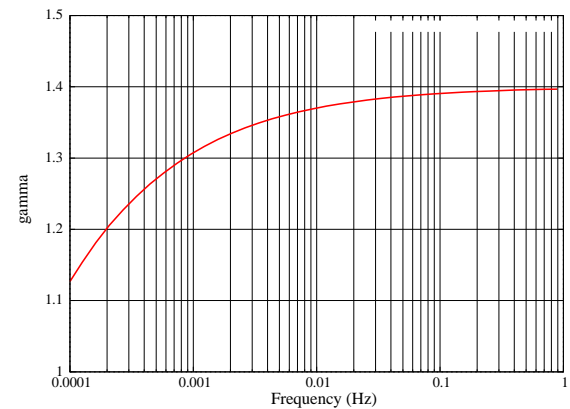
The upgrade started with Mr Kromer building a custom Hoffman box to house the new Geotech Instruments Smart24 digitizer/recorder that was linked to a Windows XP workstation with the Geotech software. The Hoffman box was installed with a power and signal distribution blocks, as shown in Figure 5. New sensor cabling was added to three of the chamber side ports and fed to the digitizer. A GPS receiver sends accurate time to the digitizer.

**Table 1: Estimates of uncertainty in chamber error analysis.**

Component	Uncertainty ( $1\sigma$ )
Piston Area	4.1%
Piston Travel	0.3%
Chamber Empty Volume	0.4%
Sensor Volume Displacement	0.2%
Heat Conduction Correction	0.1% at 1 Hz 2% at 0.02 Hz
Wall Stiffness	0.1%
Non-Ideal Gas Corrections	0.2%
Humidity Correction	0.1%
Noise in the Signal	0.1%
Ambient Pressure	<0.1%
Digitizer Calibration	<0.1%
Chamber Leaks	<0.1%
Total Standard Uncertainty	4.2 - 4.7%



**Figure 3: Plots the four values for the chamber constant. The MKS (at 0.04 Hz) value suggests other non-ideal effects may be present.**



**Figure 4: Heat conduction effects on gamma for the LANL chamber with a thermal diffusivity of  $2 \times 10^{-5} \text{ m}^2/\text{s}$ .**

A Vaisala pressure and temperature sensor package was installed, Figure 7, in one of the chamber side ports to measure the interior conditions and cabled to the digitizer. A Micro-Epsilon LVDT Gaging sensor was installed on the chamber piston, Figure 8, that enables accurate registration of the piston position and is recorded as one of the digitizer channel inputs. A frequency counter was added to the geared piston for frequency determination.

In order to have a variable frequency and amplitude source, we added a CLD Dynamics Model 316 electro-mechanical piston source, similar to that in use at the SNL FACT site. In addition to variable displacement and frequency, this unit can be driven by the calibration functions of the Smart24. The Model 316 was mounted on the back wall of the chamber as seen in Figure 9 and is powered by the controller in Figure 10.

We performed a quick linearity test on the CLD piston by using the sensor calibration feature of the Smart24 with a sinusoid source function at 0.5 and 1.0 volts driving voltage and covering the frequency range of 0.02 to 2.0 Hz. These results are shown in Figure 11. The ratio was just under a factor of two.



**Figure 5:** The Los Alamos infrasound sensor calibration chamber is shown before the upgrades.



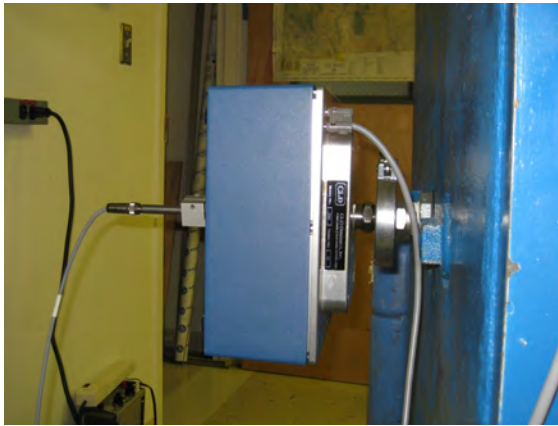
**Figure 6:** The Smart24 digitizer is shown mounted in the Hoffman box.



**Figure 7:** The Vaisala pressure and temperature display unit is shown mounted on the chamber side wall.



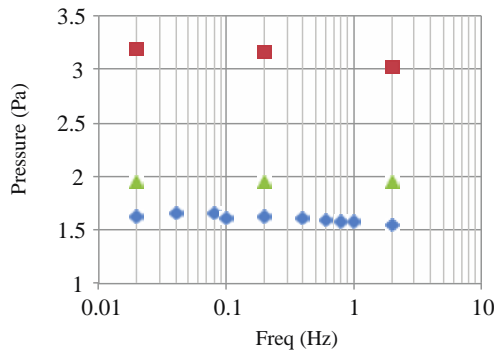
**Figure 8:** The LVDT sensor, for following the piston position is shown just above the red line.



**Figure 9: The CLD Dynamics Model 316 mounted on the back wall of the chamber.**



**Figure 10: The CLD Dynamics power unit shown on top of the chamber.**



**Figure 11 (at left): CLD 316 piston response at 0.5 volt (blue) and 1.0 volt (red) driving voltages. The ratio is displayed by the green triangles.**

### Direct Sensor Response

We have been interested in how well one could derive the sensor response, amplitude and phase, from a direct measurement of the sensor response to a step input. This could be useful and would supplement the technique of using a reference sensor. The transfer function of a sensor is, in words, the Laplace transform of the sensor output to an impulse or step input divided by the Laplace transform of the input. To approximate a step input, we have used a hypodermic syringe driven quickly by hand. For one of the sensors we calibrated, the output pressure-time history, for this source, was approximately given by

$$p(t) = \left( 1.0 - \frac{(t - t_{start})}{\tau} \right) e^{-((t - t_{start})/\tau)} \quad (2)$$

where the step starts at  $t_{start}$  and where the positive phase duration is  $\tau$  in seconds. Equation (2) is written with unit amplitude. The Laplace transform (LT) of Equation (1) is given by

$$LT(p(t)) = \frac{s}{(s + a)^2} \quad (3)$$



where  $a$  is  $1/\tau$ . The Laplace transform of a step is just  $1/s$ , so that the transfer function is then easily given by

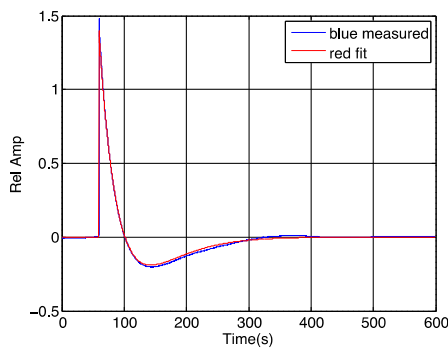
$$T(s) = \frac{s^2}{(s + a)^2}. \quad (4)$$

Equation (4) has a repeated zero of 0.0 and a repeated pole of amplitude of  $-a$ . If we substitute  $2\pi f$  for  $s$  in Equation (4), we can write for the amplitude and phase of the response as a function of frequency, after simplification

$$Amp(f) = \frac{4\pi^2 f^2}{\sqrt{((a^2 - 4\pi^2 f^2)^2 + 16\pi^2 a^2 f^2)}} = \frac{4\pi^2 f^2}{4\pi^2 f^2 + a^2} \quad (5)$$

$$Phas(f) = \arctan\left(-\frac{4\pi a f}{(a^2 - 4\pi^2 f^2)}\right). \quad (6)$$

In Figure 12 we show the measured sensor response to the step input and the fit given by Equation (2). If one looks closely at the rise of the measured sensor response to the step, one can see that a more rapid step source would be better. In Table 2 we show phase of the sensor response as a function frequency as given by Equation (6) and from measurements. The analytic result compares favorably to actual measurements for this sensor.



**Figure 12: The measured sensor response (blue) and the fit (red) are shown**

**Table 2: Comparison of response phases**

Frequency (Hz)	Phase analytic (degrees)	Phase reference (degrees)
0.02	21.4	20.9
0.04	10.8	11.5
0.05	8.6	9.4
0.06	7.2	7.9
0.1	4.3	4.8
0.2	2.2	2.3

This initial experiment in the derivation of a sensor response from a measured step response has shown some promise. The need for a faster impulse source has been shown. The direct approach here requires that the measured sensor response be fit with an analytic function whose Laplace transform is determinable. This leads directly to a form from which the amplitude and phase are easily obtained or can be found with Maxima or Mathematica.

### FUTURE WORK

As mentioned above, we had to move the chamber to a new location at the end of FY11. This move has caused a bit of a delay in our planned work. Two potential locations have proved unworkable; a third is being explored. When the chamber is relocated, we will put it all back together and began a checkout process in order to get back to where



we were before the move. We still need to get the Sensor Testing Software from SNL that we hope to apply to our operation. (At this time it is not quite ready for release.) Then we can get back to doing an annual check on some sensors for SNL. For step function generation, we want to control the CLD Model 316 with the Smart24 step calibration signal to see if faster rise times can be achieved. We will also explore other methods of generating step functions with faster rise times.

### **SUMMARY**

We have documented past work on the determination of the calibration constant of the LANL infrasound sensor calibration chamber done with collaboration of SNL. This included an uncertainty analysis. A summary of equipment upgrades and measurements was provided as well. Finally we discussed some aspects of analytic approaches to sensor response determinations.

### **ACKNOWLEDGMENTS**

The detailed analysis of the chamber output and error budget was supported in part by the US SMDC and the National Center for Physical Acoustics of the University of Mississippi. The upgrades were made possible through a research grant from SMDC and administered by NCPA. Dr. Harold Parks of the Primary Electrical Standards Laboratory at Sandia National Laboratory performed some of the dimensional measurements, performed the detailed error analysis and provided important technical advice. Mr. Richard Kromer, formerly of SNL and now at Array Information Technologies, designed and implemented the upgrades and made other improvements. His contributions were essential to making the upgrade process successful. We thank Dr George Randall for insightful discussions on seismic and infrasonic sensor response and other analysis topics. Finally, thanks to H. V. Parks for information gleaned through personal communication in 2007 regarding his uncertainty analysis and chamber measurements.

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